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HYDROPHONES SUITABLE FOR DETECTING AIRCRAFT

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ABSTRACT

The Navy has need of a sensitive (air) microphone, located outside the hull of a submarine, which will withstand the hydrostatic pressure of the ocean during submergence, and then perform normally in air after the boat surfaces.

The self-noise of the hydrophone and preamplifier must be low enough so that a distant aircraft can be heard. Depending on the desired listening distance, a choice of designs is available.

ADMINISTRATIVE INFORMATION

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LIST OF ILLUSTRATIONS

HYDROPHONES SUITABLE FOR DETECTING AIRCRAFT
Second Type of Design
30 December 1994

The Navy has need of a sensitive (air) microphone, located outside the hull of a submarine, which will withstand the hydrostatic pressure of the ocean during submergence, and then perform normally in air after the boat surfaces.

One way to protect such a microphone is by using moveable hatch covers, etc. A different approach is to use a (water) hydrophone inherently designed to withstand hydrostatic pressure, and adapt it to function additionally as a sensitive air microphone. This is the approach to be described in this memo.

In the report of 1 December 1994, "Microphones Suitable for Detecting Helicopters," a discussion was given on the capability of a cylindrical ceramic tube to handle the problem. It was shown that with:

sensitivity M = -197 dB below 1 volt/μPa,
capacitance Co = 14.4 nF,
loss tan $\delta = 0.02$, and
resonance freq. fr $\simeq$ 70,000 Hz,

the microphone alone had a self-noise at 20 Hz of 39 dB above $1\mu Pa^2/Hz$. However, with a preamplifier and a low-pass filter cutting off at 100 Hz, the integrated self-noise of the total system has an average value per Hz of 47 dB above $1\mu Pa^2/Hz$. This rises with the bandwidth by about 20 dB to a level of 67 dB above $1\mu Pa^2$. This microphone/hydrophone might be able to barely detect a helicopter at a distance of 15 km. However, it is a marginal design. (See p. A-6, last paragraph).

Therefore, it was desired to see how much improved performance could be obtained using other microphone/hydrophone designs. There exists in nature a Gain x Bandwidth Law. This says that if you can somehow attach a lever to a bar of ceramic which expands/contracts, and change this motion into a bending motion, thereby greatly lowering the original resonance frequency fr_1 (say 70 kc) to the new resonance frequency fr_2 (say 7 kc), the 10:1 reduction in

useful bandwidth will be accompanied by a 10:1 increase in the "gain" or sensitivity M, which is a 20 dB increase in M (see figure 1).

Such a lever exists in the piezoelectric transducer technology. It is called a bimorph. A variant is the unimorph. These are analogous to a bimetallic thermostat which coils or uncoils with temperature change. One has to choose, from available ceramic bars and discs, a ceramic length or diameter, thickness, and composition which will give the best compromise of fr, M, tan δ, and capacitance. Usually this requires the use of a few small microphones in a series-parallel arrangement. A single large diameter (say 3") microphone would have too low an fr and thus too narrow a bandwidth. Hence six small microphones are often used instead (see figure 2).

First we will discuss a design using only <u>one</u> bimorph microphone. The design uses a bimorph comprising two ceramic discs of PZT-5H (Lead Zirconate Titanate) material, having a diameter of 0.75" and each disc a thickness of 7.5 mils, with a metal disc of 6 mil thickness separating them. Thus the total thickness of the sandwich is 21 mils. These bimorphs are manufactured in the U.S.A. and are commercially available from the Morgan Matroc company (Ref. 1). A choice is offered of discs in series or discs in parallel. The series bimorph has been chosen.

Each plate will have a sensitivity M = -185 dB below 1 volt/μPa. This is a 12 dB increase over the ceramic cylinder. But in addition the two plates are connected in series. This raises the bimorph level by another 6 dB to:

M = -179 dB below 1 volt/μPa. So the result would now be an 18 dB increase over the cylinder's value of -197 dB, if the air cavity beneath the bimorph had an infinite volume. The bimorph capacitance C = 22.4 nF. The ceramic loss tangent is still tan $\delta = 0.02$. The resonance frequency is now $fr_2 \simeq 4100$ Hz.

The increase in M is a true Signal/Noise increase of 18 dB since the ceramic self-noise level did not increase. But since the air cavity has a finite volume, this adds a stiffness to the bimorph stiffness thereby reducing the effective sensitivity to about M = -181 dB, a 2 dB reduction.

So we have C = 22.4 nf. At 20 Hz, Xc = 355,000 Ω, tan $\delta = 0.02$, and $R_h = 7110\ \Omega$.

Now, the ceramic self-noise S_h is controlled by the resistance R_h. This noise is also called thermal noise or Johnson noise and is expressed as $volt^2/Hz$ (see 1 December 1994 report, which is the Appendix). Then at 20 Hz we have:

$$S_h = 4\ KT\ R_h\ volt^2/Hz \text{ which is } 114 \times 10^{-18}\ V^2/Hz \text{ or } -159 \text{ dB below } 1\ volt^2/Hz.$$

We can convert this to acoustic dimensions by subtracting the decibel value of M^2 referred to $volt^2/\mu Pa^2$ (M and M^2 have the same decibel value of -181 dB) and obtaining

$$S_h^{'} = 22 \text{ dB above } 1\mu Pa^2/Hz \text{ at } 20 \text{ Hz}.$$

This is a 17 dB lower self-noise floor than the cylinder design, which was 39 dB above $1\mu Pa^2/Hz$. However, the preamplifier self-noise at 20 Hz is about -146 dB below 1 $volt^2/Hz$ or, in acoustical units, 35 dB above $1\mu Pa^2/Hz$. Here the preamp noise is the controlling factor and we can neglect the microphone noise (see figure 3). As we expand the bandwidth beyond 1 Hz, the noise would increase by 10 dB per decade if the response were flat. See figure A-6 for the actual law.

Helicopter Noise was discussed in the 1 December 1994 report, "First Type of Design." There it was shown that a typical commercial helicopter radiates a sound pressure level of about 75 dB vs 20μPa (0 dB for air acoustics) at a distance of 1 km. At a distance of 15 km the level would be down nearly 24 dB to a level of 51 dB vs 20μPa. Alternatively this can be written (adding 26 dB) as a sound pressure level of 77 dB vs 1μPa and also as a sound power level of 77 dB vs $1\mu Pa^2$ (0 dB for self-noise measurements).

Some additional information comes from a Russian journal (Ref. 2) where the bottom figure on page 855 (our figure 5) shows that at large distances (e.g., 15 km) probably the only sounds that can be heard will be the first four tonals, viz. 25, 50, 75, and 100 Hz. Now in addition, Ref. 3 from the *Journal of the Acoustical Society of America* provides curves showing the atmospheric absorption of sound as a function of humidity. The reduction of the sound level at 15 km for a tone of 50 Hz is about 1.5 dB (our figure 6). [This loss equals 150 dB $\cdot$ 10^{-2}.] This would reduce the helicopter sound level of 51 dB (mentioned above) to 49.5 dB vs 20μPa assuming that the received sound level was being controlled by the 50 Hz region. This can be written alternatively as 75.5 dB vs 1μPa (pressure) or vs $1\mu Pa^2$ (power), using the 26 dB adjustment factor.

Now the self-noise S_h' of our preamp (the controlling factor) was 35 dB above $1\mu Pa^2/Hz$ for a 1 Hz bandwidth in the 20 Hz region. As we expand the bandwidth the noise increases. But if we use a bandpass filter which cuts off just above 50 Hz, the noise level in the band 20 Hz to 50 Hz will increase by less than 15 dB, giving a broadband noise of about 45 dB above $1\mu Pa^2$. If we expand the band to 100 Hz, the noise level will increase by less than 19 dB, giving a broadband value of Johnson noise of about 50 dB above $1\mu Pa^2$. But the 100 Hz tone is now attenuated atmospherically by about 4.5 dB, giving us little if any improvement over the 50 Hz cut-off situation. Thus the single bimorph has provided sufficient sensitivity and quietness for the problem. That is, the helicopter-radiated sound is on the order of 49.5 dB vs $20\mu Pa$ or 75.5 dB vs $1\mu Pa$ or vs $1\mu Pa^2$. This is far above the Johnson noise level of 50 dB above $1\mu Pa^2$.

Multiple Microphones. How much increase in sensitivity can be attained without resorting to extraordinary measures? Let us try three bimorph-microphones in series, which raises the level of M = -181 dB by 9.5 dB to a sensitivity

$M = -171.5$ vs 1 volt/μPa
$C = 7.5$ nF.

The OD of the three bimorphs is less than 3" and will look much like the three-microphone photo in figure 2.

Now, the ceramic self-noise at f = 20 Hz is given by tan δ and C. Then $1/\omega C$ or $X = 1.06 \times 10^6\ \Omega$, $\tan\delta = 0.02$, and $R_h = 21{,}220\Omega$. The ceramic's thermal noise or Johnson noise at 20 Hz in volts^2/Hz is given by (see Appendix):

$S_h = 4\ KT\ R_h$ volt^2/Hz which is $340 \times 10^{-18}\ V^2/Hz$ or -155 dB vs 1 volt^2/Hz.

We can convert this to acoustic dimensions by subtracting the decibel value of M^2 referred to volt$^2/\mu Pa^2$ (M and M^2 have the same decibel value of -171.5 dB) and obtaining

$S_h' = 16.5$ dB above $1\mu Pa^2/Hz$ at 20 Hz.

This is a 22.5 dB lower self-noise floor than the cylinder design, which was 39 dB above $1\mu Pa^2/Hz$. However, the preamplifier self-noise at 20 Hz is about -146 dB below 1 volt^2/Hz or, in acoustical units, 25.5 dB above $1\mu Pa^2/Hz$. So the preamp noise is 9 dB higher than the

microphone noise. Thus, the preamp noise is the controlling factor and we can neglect the microphone noise (see figure 3).

To recapitulate, a single bimorph produced an M of -181 dB vs 1V/μPa and, with a preamp, a Johnson noise at 20 Hz of 35 dB above $1\mu Pa^2/Hz$.

A group of three bimorphs in series (see figure 2) produced an M of -171.5 dB vs 1V/μPa and, with a preamp, a Johnson noise at 20 Hz of 25.5 dB above $1\mu Pa^2/Hz$.

If a further increase in S/N is desired, it could be accomplished by four microphones in series giving an additional 2.5 dB of gain, with a small increase in ceramic self-noise. Other groupings can be seen in figure 2, giving further increases in sensitivity M.

Metal Bellows. So far we have discussed a design using a flexing diaphragm (the bimorph) mounted over a cavity having an ample volume of air. The cavity stiffness $\left(K_{ac} = \gamma P_o / V_{ol}\right)$ reduces M by about 2 dB. An ordinary air microphone when submerged in the ocean would be crushed by the hydrostatic pressure. Our design solves the problem by using an oil-filled metallic bellows (figure 4) which expands during submergence of the boat, compressing the enclosed air so that all hydrostatic pressures are balanced out. To protect the bellows from the environment of sea water, a rugged second bellows shields the first, and goes into compression during submergence. This second bellows is also filled with oil. No sea water touches the delicate parts of the microphone. When the microphone rises out of the ocean, the first bellows contracts, thus providing the cavity once more with "soft air" at atmospheric pressure P_o, and the second bellows expands to its normal shape. This is shown in figure 4 where the submerged condition is shown on the left and the surfaced condition is shown on the right. The required metallic bellows are available from at least two companies (see Ref. 4).

SUMMARY

We will call the sound pressure level at a distance of one km from a radiating aircraft 75 dB vs 20μPa, which is 101 dB vs 1μPa. This figure refers to the noise-signal radiated by commercial helicopters in the band 10 Hz to 1000 Hz (see p. A-5).

If we change the distance to 15 km, we lose 24 dB due to spreading loss giving 77 dB vs 1μPa (see p. A-6). But in addition, the atmospheric attenuation makes unusable all frequencies above about 100 Hz.

If then we cut off at 100 Hz (see figure 5), the original radiated noise-signal at one km is perhaps reduced 6 dB, from 101 dB to 95 dB. The spreading distance of 15 km reduces the noise-signal level to 71 dB.

We lose an additional 4 dB due to atmospherics (see figure 6). This gives us at 15 km a noise-signal level of about 67 dB vs 1μPa. This is ordinarily given as 41 dB vs 20μPa, by the aircraft community (a 26 dB adjustment factor).

If the Johnson noise-level or self-noise level is about 50 dB vs $1\mu Pa^2$ (p. 4, top paragraph), our design will do well since our noise-signal level is about 67 dB vs 1μPa. If the Johnson noise-level is 70 dB vs $1\mu Pa^2$ (p. A-6, last paragraph), the design will fail.

Reviewing the "First Type of Design" (see Appendix), the simple small ceramic tube with a self-noise level of 70 dB vs $1\mu Pa^2$ (see p. A-6) can be modified to reduce this noise level. The length and the diameter can be increased to say 2" by 2" (wall thickness to be calculated). The bandwidth will be reduced and so the sensitivity will be increased and the self-noise reduced.

Alternatively, a large Bender Bimorph can be used, with a diameter of about 3" and a thickness of about 1/4". Again, the bandwidth will be reduced, the sensitivity increased, and the self-noise reduced.

These designs can be made to override the Johnson noise of 70 dB vs $1\mu Pa^2$.

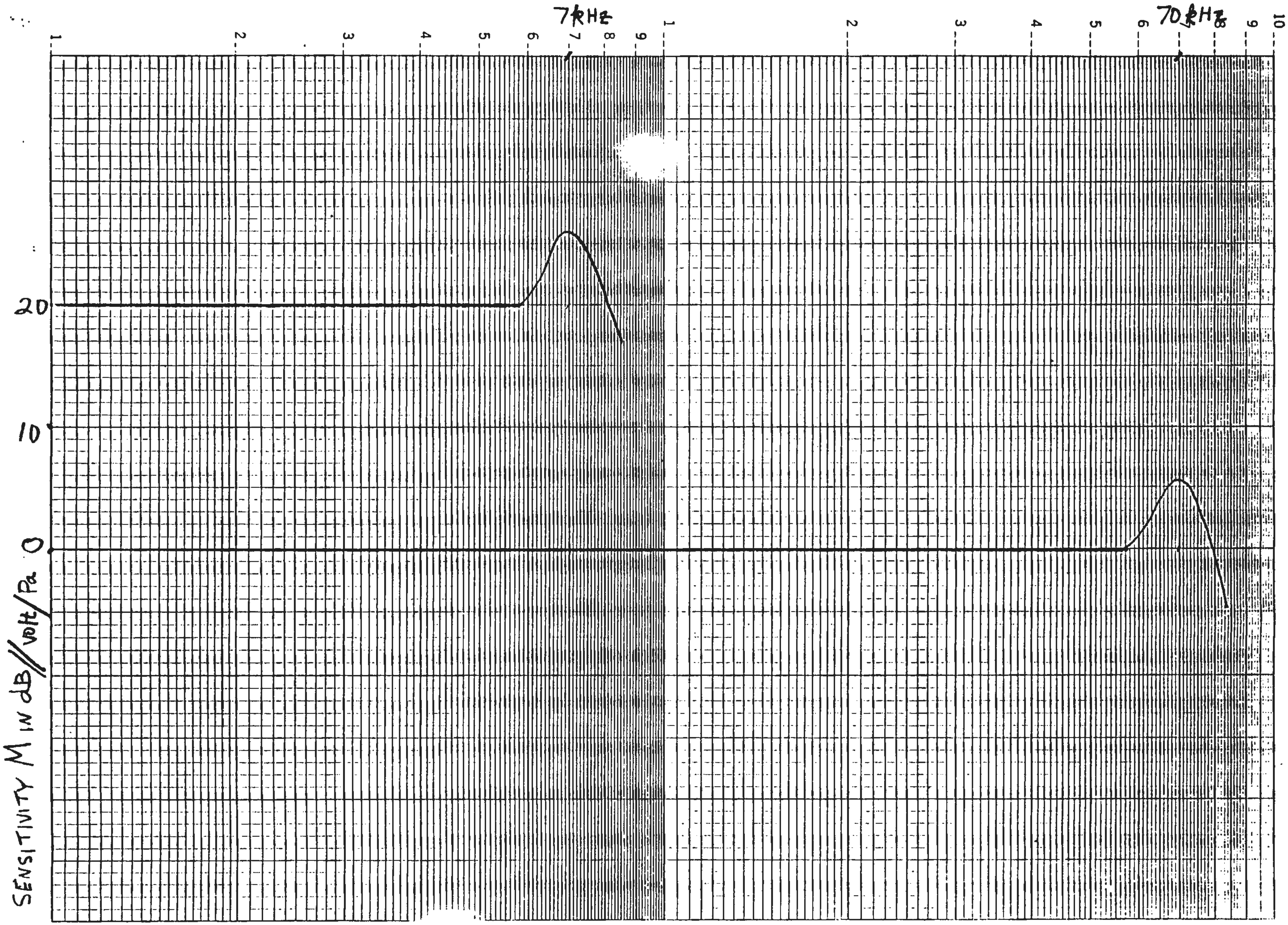


Figure 1. Example of Gain x Bandwidth Law for Two Microphone Designs

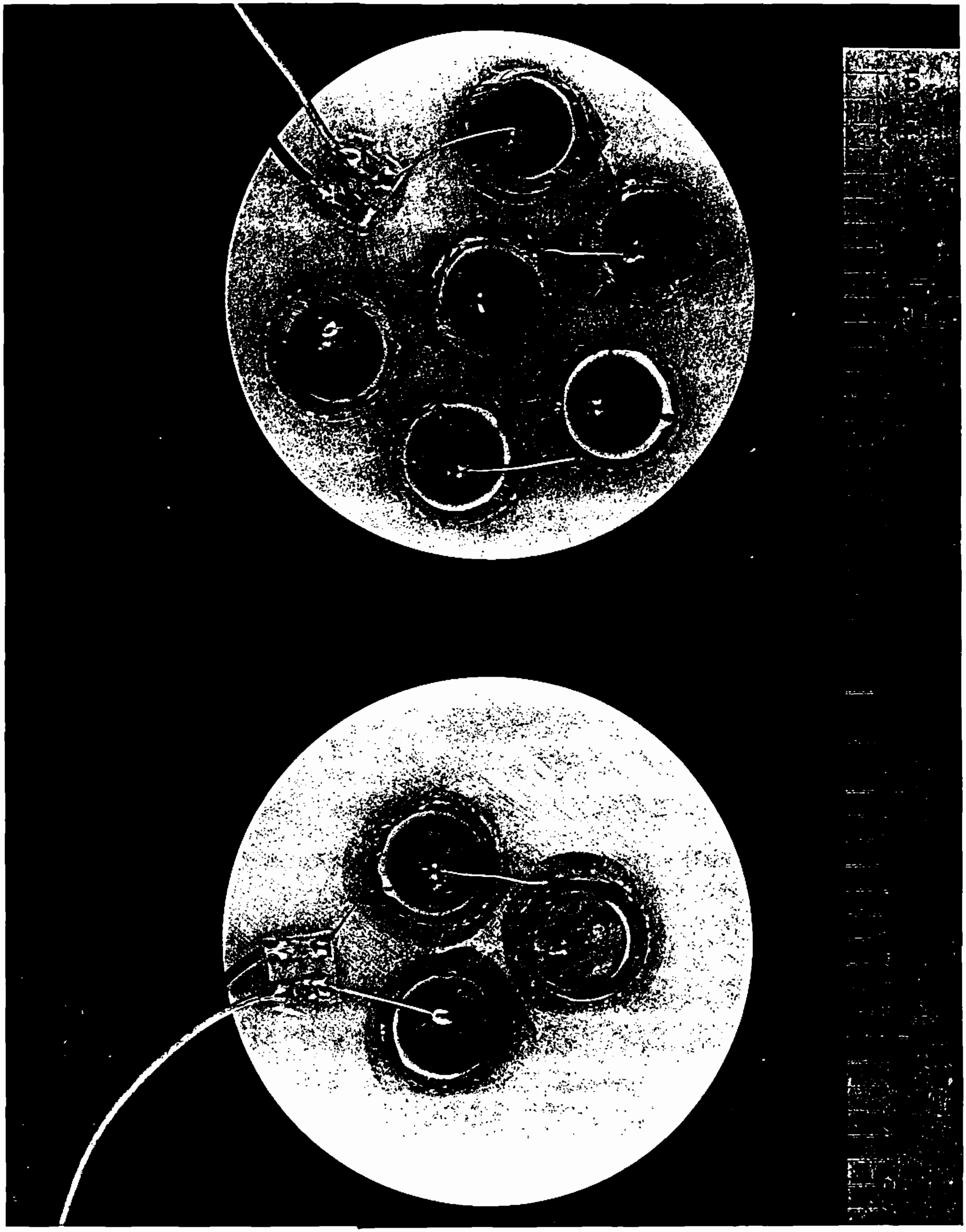
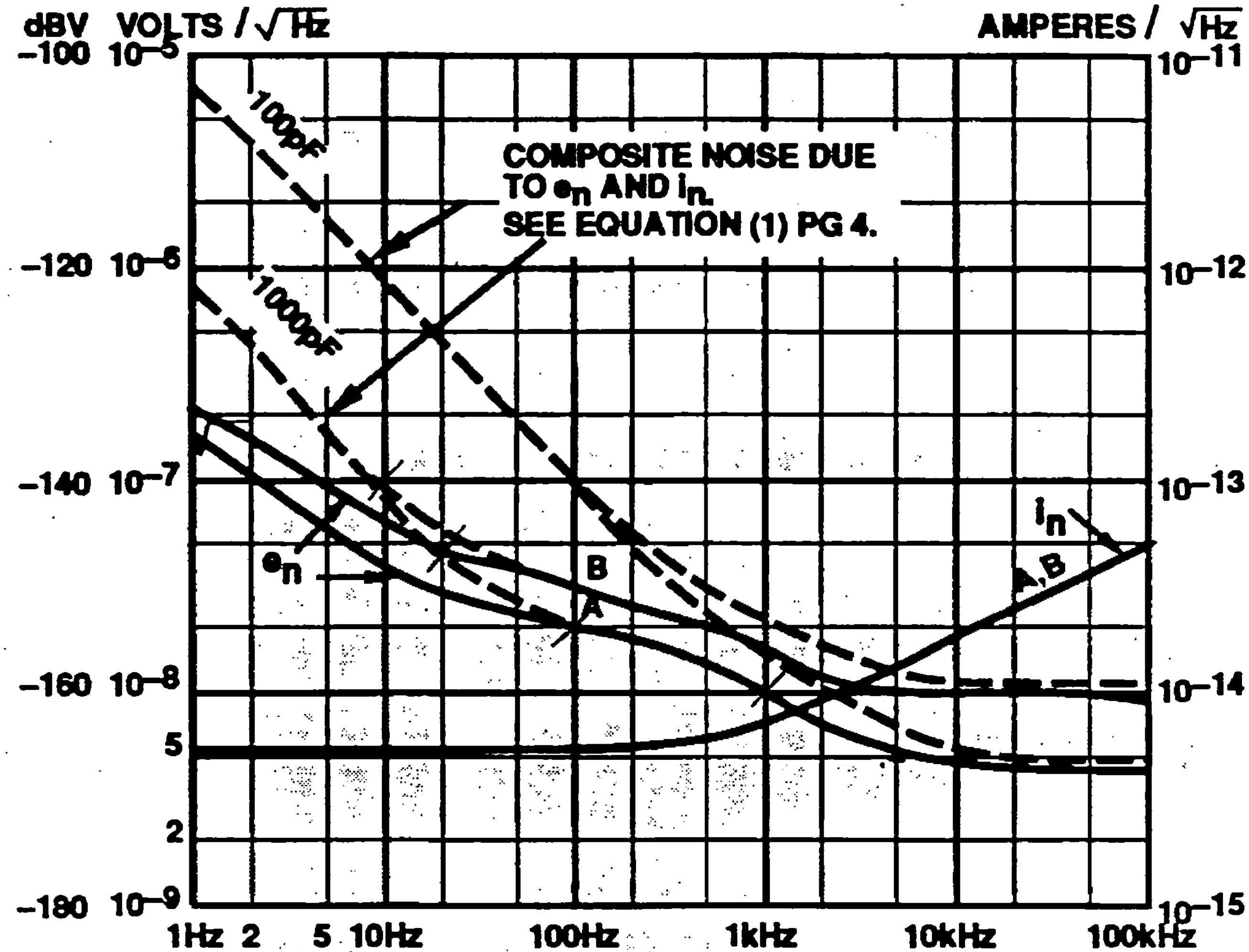


Figure 2. Arrangement of an Array of Three Microphones and an Array of Six Microphones

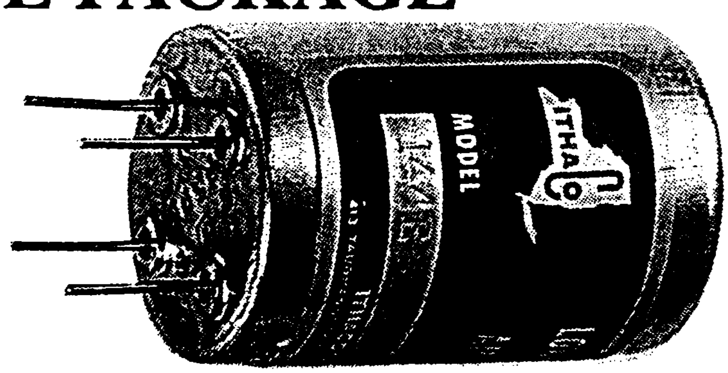
100 SERIES ULTRA HIGH IMI



✓ A refers to Models 143/144, B refers to Model 125

Figure *Noise Voltage and Noise Current For High Impedance Voltage Preamplifiers, 1 Hz BW*

E PACKAGE



PIN CONNECTI

O OUTPUT
B POWER
I INPUT
G GROUND

CAN SIZE 29mm dia, 41mm long (1.13" Dia., 1.6" long)

Figure 3. Low-Noise Preamplifier (ITHACO Model 143/144)

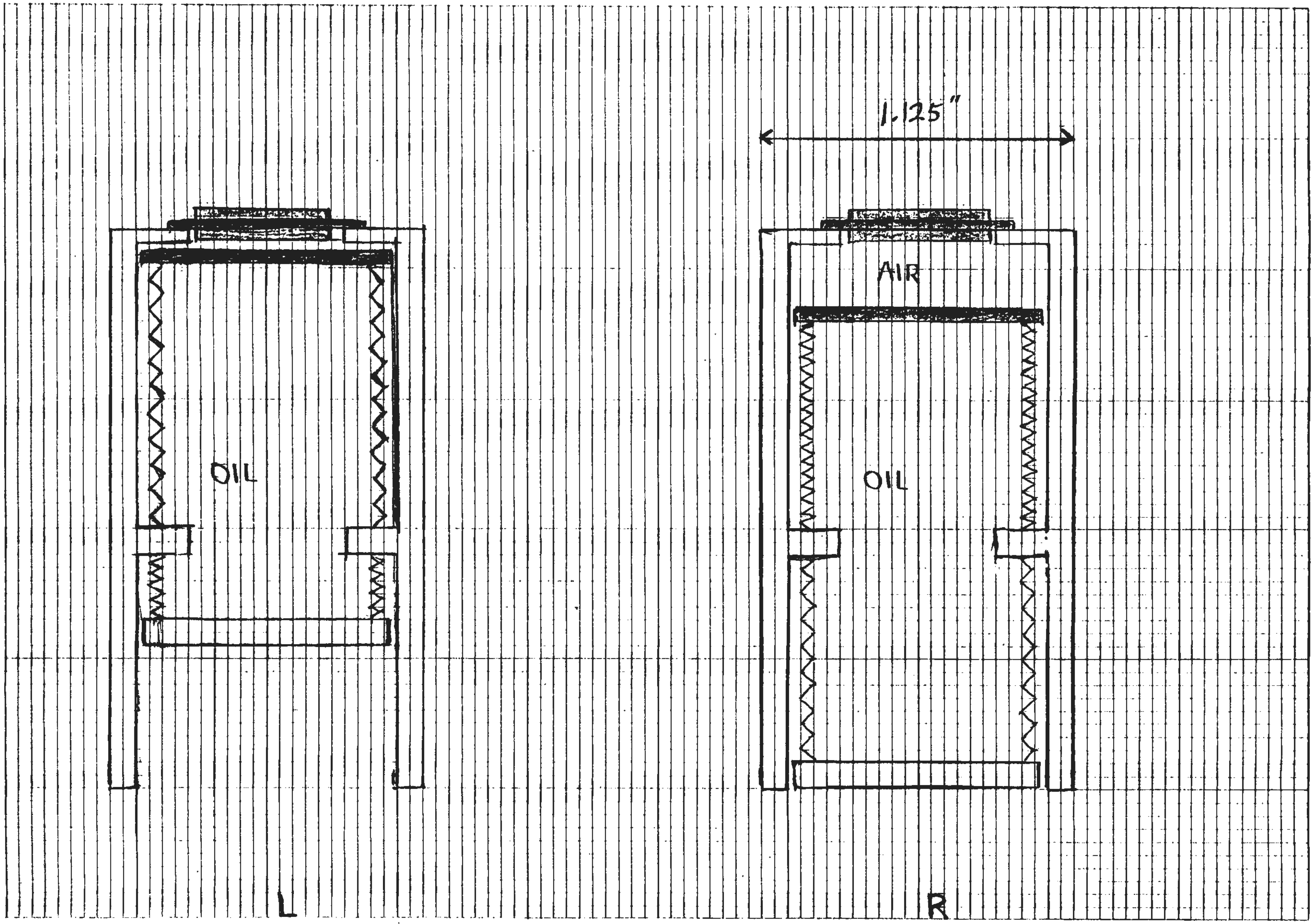


Figure 4. Oil-Filled Metallic Bellows

Left: Under Great Water Pressure Right: At Atmospheric Pressure

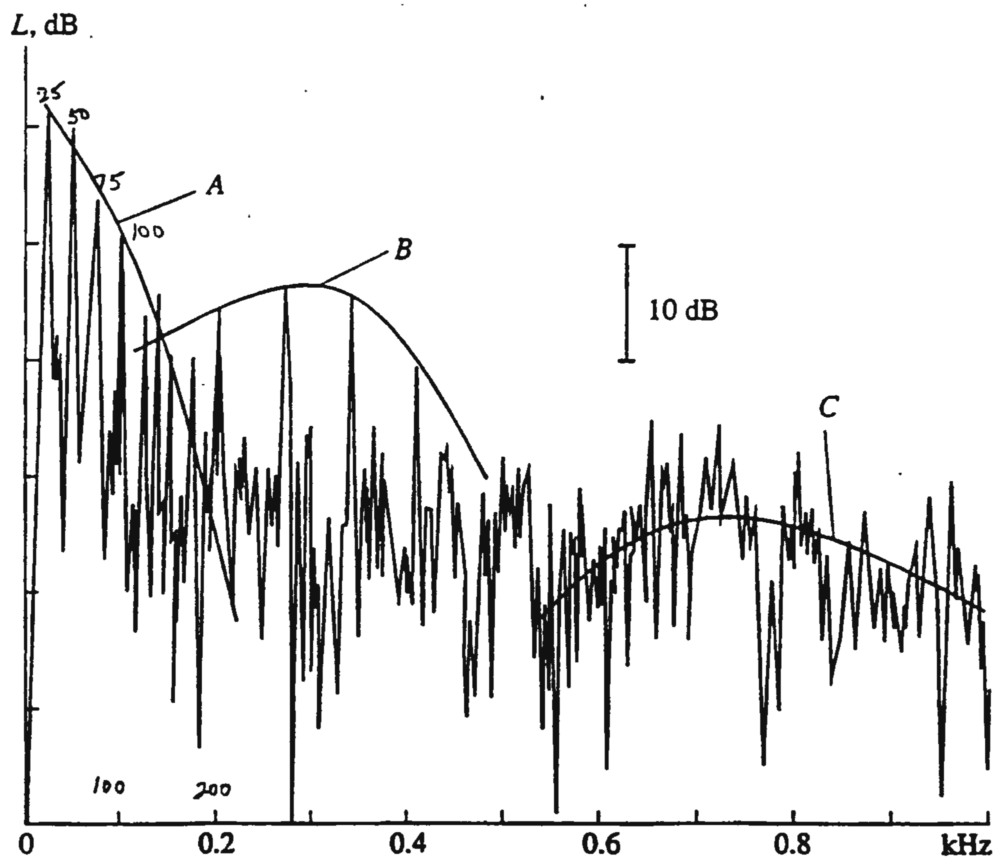


Fig. 5. Instantaneous sound pressure spectrum in narrow frequency bands ($\Delta f = 12.5$ Hz) with the frequency scale expanded in the range of 0 to 1000 Hz. A Mi-28 helicopter with standard tail rotor for $\tau = \tau_{PNLTM}$, $H = 150$ m, $\bar{V} = 0.325$. (*A*) MR harmonics, (*B*) TR harmonics, (*C*) broadband noise.

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Figure 5. Helicopter Tonals Below 200 Hz

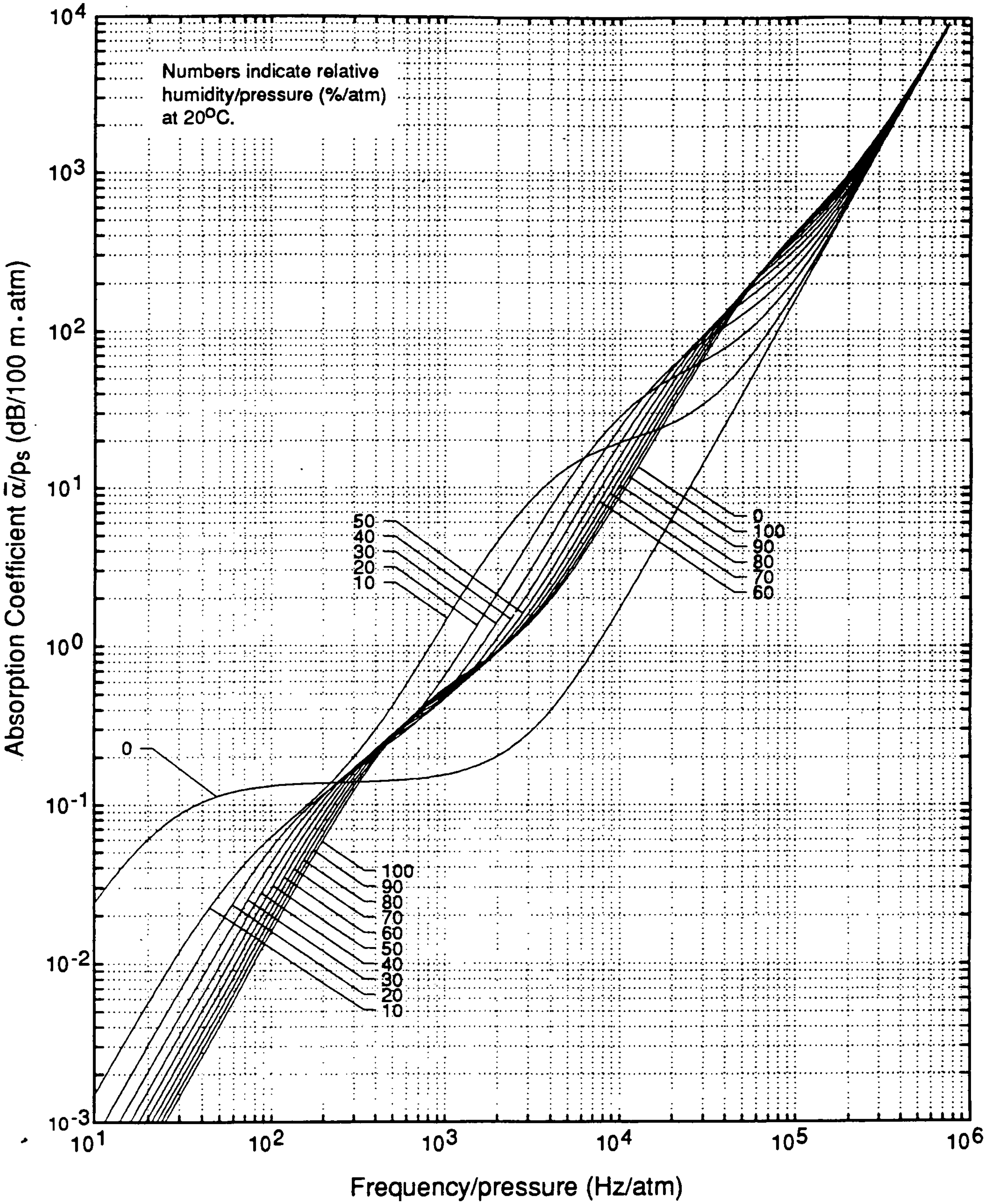


FIG. 1. Sound absorption coefficient per atmosphere, SI units, for air at 20°C. The abscissa is frequency/pressure, and the parameter is relative humidity/pressure in the range 0 to 100%/atm.

Figure 6. Absorption vs Frequency for Various Humidity Values

APPENDIX

MICROPHONES SUITABLE FOR DETECTING HELICOPTERS
First Type of Design
1 December 1994

Piezoelectric and condenser microphones or hydrophones have very similar electromechanical analog circuits. The piezoelectric microphone/hydrophone will be chosen for the discussion of the general problem. Figure A-1 shows the most useful analog circuit for our purposes. A piezoelectric ceramic transducer is being described.

F_{gen} = incident sound pressure p times area A of receiving face,

R_{rad} = radiation resistance,

R_{loss} = mechanical losses,

M = mass of moving "diaphragm,"

C_m^E = mechanical compliance when electric terminals are short-circuited,

N = electromechanical turns-ratio (transformer),

C_b = electrical capacitance when mechanical terminals are open-circuited ("blocked"),

C_o = electrical capacitance when mechanical terminals are short-circuited ("free"), and

G_b = leakage conductance across the blocked capacitor.

When the resonance frequency is much higher than the band being used, this transducer is called a stiffness-controlled hydrophone or microphone. Thévenin's Theorem allows the circuit to be rewritten as figure A-2. Note that C'^E_m is the value of C^E_m after it has moved to the right through the turns-ratio N:1. Likewise, F_{gen} becomes E_{OC}. The two capacitors in parallel will now be called C_O (the "free capacitance"). E_{OC} can be rewritten as M.p or volts/μPa • μPa = volts.

E_{OC} is the open circuit voltage measured at right-hand terminals. The leakage conductance G_b is now evaluated as its inverse, the loss resistance R_b. These components are being discussed because they determine the self-noise of the microphone in an extremely quiet

location. If the self-noise is too high, the microphone will not be able to detect a far-off helicopter.

A useful relationship is G_b/B_o or $G_b/\omega C_o = \tan\delta$ where δ is the phase angle between G and B_o (see figure A-3). This can also be written as $1/R_b \,//\, 1/X_o = X_o/R_b = \tan\delta$. And then the parallel resistance R_b can be converted to a series resistance R_h by a well-known relation $R_h \simeq X_o^2/R_b$ or $R_h \simeq X_o \tan\delta$ (see figure A-4).

It can be shown that useful designs of microphones can be made using a hollow cylinder or sphere, whose self-noise is less than either sea-state zero (200μPa at 1 kHz; see figure A-5) or than atmospheric noise near the sea surface (which is about the same as sea-state zero on a quiet windless day). Such microphones can operate equally well as hydrophones, even at great depth, so no unusual design features need be created in order for the microphone to withstand the sea pressure after submergence of the boat.

As an example (see Addendum), consider a PZT-5 ceramic (Navy Type II) air-filled cylinder of dimensions:

$$\begin{aligned} \text{OD} &= 0.75'' \\ \text{L} &= 0.55'' \\ \text{wall t} &= 0.0625'' \end{aligned}$$

radially poled and with capped ends.

The sensitivity M is 145.6×10^{-6} volts/Pa or 145.6×10^{-6} volts/10^6μPa.

So, M = -196.7 dB below 1 volt/μPa, and M^2 = -76.7 dB below 1 volt^2/Pa^2.

The capacitance is C_o = 14.4 nF and the dissipation factor or $\tan\delta = 0.02$.

1. At f = 100 Hz, the reactance $1/\omega C_o$ (see page 3) or $X_o = 110{,}000\Omega$.

The series loss resistance R_h is 2200Ω. This generates thermal noise or "Johnson Noise," in volts^2/Hz, given by

$S_h = 4K_b T R_h$ volts^2/Hz ,

where

K_b = Boltzman's constant = 1.38×10^{-23} Joules/^oK and

T = absolute temperature $\simeq 290^oK$.

Now when

$R_h = 2200\Omega$, then for a $\Delta f = 1$ Hz (implied in the formula),

$S_h = 35.2 \times 10^{-18}$ v^2/Hz or -165 dB below 1 volt^2/Hz .

We can convert this to acoustic dimensions by dividing by sensitivity squared or M^2 in volts^2/Pa^2. (1Pa = 1N/m^2 or 10 dynes/cm^2.)

Now, our M = 145.6×10^{-6} v/Pa , or -77 dB // 1v/Pa .

So, $M^2 = 21.2 \times 10^{-9}$ v^2/Pa^2 , or

-77 dB // $1v^2/Pa^2$.

Then $S_h' = S_h/M^2 = \dfrac{35.2 \times 10^{-18}}{21.2 \times 10^{-9}} = 1675 \times 10^{-12}$ Pa^2/Hz or -88 dB vs $1Pa^2$/Hz .

Alternatively S_h' = 1675 (μPa)^2/Hz, which (because we added 120 dB, to change Pa^2 to μPa^2) becomes 32 dB above 1μPa^2/Hz.

(For people familiar with the sound of Sea State zero, shown in figure A-5, at 100 Hz this noise level is 29 dB below sea state zero.)

2. If we repeat the calculations at f = 1000 Hz, the reactance $1/\omega C_o$ becomes 11,000Ω. Tan δ is still 0.02. So the series loss resistance R_h is now 220Ω, making $S_h = 35.2 \times 10^{-19}$ v^2/Hz or -175 dB below 1 volt^2/Hz. But the microphone sensitivity remains flat: M = 145.6μv/Pa or -77 dB // 1v/Pa. So, converting S_h, which is -175 dB vs 1 v^2/Hz, we get S_h' =168μPa^2/Hz or S_h' = 22 dB above 1μPa^2/Hz.

(This is about 24 dB below sea state zero at 1000 Hz, as seen in figure A-5.)

3. If f = 20 Hz, $1/\omega C_o = 550{,}000\Omega$, tan δ = 0.02.

Then

$R_h = 11{,}000\Omega$,

$S_h = -158$ dB below 1 volt^2/Hz, and

$S_h^{|} = 39$ dB above $1\mu Pa^2$/Hz.

Microphone Plus Preamplifier. A good FET preamplifier has a noise figure of about -146 dB below 1 volt^2/Hz at 20 Hz (see figure A-6). This FET in series with the hydrophone/ microphone would dominate the self-noise of the system. The equivalent acoustical noise level at 20 Hz is then 51 dB above $1\mu Pa^2$/Hz. ($M^2 \simeq -197$ dB vs $1v^2/\mu Pa^2$).

In order to relate power/Hz or μPa^2/Hz to sound pressure p in μPa, it should be noted that at 1000 Hz, sea state zero is about 46 dB above $1\mu Pa^2$/Hz. An equivalent 1 kHz sine wave would also have a sound pressure of 46 dB above 1μPa, which is approximately 200μPa.

Now for sound in air the reference level or 0 dB is standardized at 20μPa (which is 0.0002 dyne/cm^2), where 1 Pascal is 10 newtons/meter^2. This would be 26 dB above 1μPa on the grid of figure A-5, so sea state zero at 1 kHz (46 dB) is 20 dB louder than the standard reference level in air (which is approximately the minimum level of hearing at one kHz). And the noise level of sea state zero is approximately the noise level in a quiet living room.

Other Air Microphones. Conventional microphones designed for use in air comprise: piezoelectric bimorphs, electrets, dynamic (electromagnetic) microphones, and others. A typical piezoelectric bimorph microphone has a sensitivity M of about -170 dB vs $1v/\mu$Pa, which is about 27 dB more sensitive than the cylindrical hydrophone discussed above. This is primarily due to the narrowing of the cylinder's bandwidth by virtue of the lever action of a bimorph. That is, there is always a Gain x Bandwidth law which says that if the bandwidth is reduced 100:1, the gain or M is increased by 100:1 or 40 dB. So within this reduced bandwidth the typical air microphone could have a 27 dB higher sensitivity M and therefore, since the Johnson noise or self-noise is unchanged, a much increased S/N ratio for the system of microphone plus preamplifier.

However, if the cylindrical hydrophone system's self-noise is already lower than what is required by the problem, then it is a perfectly acceptable microphone. So the next thing to investigate is the noise level of a helicopter flying in the neighborhood of a microphone array.

Helicopter Noise. Information on the acoustical detectability of American military helicopters was unattainable. However, telephone conversations with people at Sikorsky and at NASA Langley (Ref. 5) yielded useful information on commercial helicopters. Thus, the noisy Bell "Huey" has a main rotor fundamental of 11 Hz, with harmonics at 22, 33, 44, etc. The strength of these harmonics diminishes rapidly as the frequency increases but then broadband noise becomes important, up to 1000 Hz. The Black Hawk is quieter, with tones at 17, 34, 51 Hz, etc. The MI 24 radiates 23, 46, 69 Hz, etc.

In general, the important region of helicopter noise is considered to be the band from 20 Hz to 1000 Hz. The Sikorsky S-76 at a height of 100 feet can be heard with the ear at a distance of about 1 km with a level of 75 dB vs 20μPa (0 dB).

An Apache can be heard with the ear at 3 or 4 miles distance. A typical "flyover pattern" is shown in figure A-7. This shows that an MD 500E with a rotor tip speed of 700 feet/sec, height unspecified, radiated a level of 92 dB as received by a microphone on the ground directly beneath the helicopter. When approaching at 80 knots, the helicopter put out a level of 65 to 70 dB one mile away (40 seconds, in time). This can be detected at 1 km by the cylindrical ceramic hydrophone, as will now be shown.

We can break up the receiving band of the microphone into three regions, centered around 20 Hz, 100 Hz, and 1000 Hz. The total receiver system noise, microphone plus preamplifier, is about:

1. 20 Hz -146 dB below 1 volt^2/Hz (electrical units)

   or

   +51 dB above 1μPa^2/Hz (acoustical units)

2. 100 Hz -154 dB (electrical)

   or

   +43 dB (acoustical)

3. 1000 Hz -160 dB (electrical)

   or

   +37 dB (acoustical)

This gives a self-noise average value, over the band, equal to 44 dB above $1\mu Pa^2$ for a bandwidth $\Delta f = 1$ Hz.

If the bandwidth is increased to $\Delta f = 1000$ Hz, the integrated noise level rises by a 30 dB increase. So the total self noise over the band is approximately 74 dB above $1\mu Pa^2$. If the helicopter sound pressure level is 75 dB vs $20\mu Pa$ (0 dB for air acoustics) this is alternatively a sound <u>pressure</u> level of 101 dB vs $1\mu Pa$ which is also a sound <u>power</u> level of 101 dB vs $1\mu Pa^2$ (0 dB for self-noise measurements). At a distance of 15 km the geometrical attenuation is 24 dB. So the sound power level for $\Delta f = 1000$ Hz is now 77 dB vs $1\mu Pa^2$. This would seem adequate to override the 74 dB of self noise.

However, some additional information contained in the January 1995 issue (Ref. 3) of the *Journal of the Acoustical Society of America* gives the relation between sound absorption in air and humidity. This shows (our earlier figure 6) that at 1000 Hz the attenuation at 15 km is about 70 dB, thus reducing the 77 dB value to 7 dB vs $1\mu Pa^2$. This is far below the required level of at least 74 dB vs $1\mu Pa^2$.

If we now use a low pass filter cutting off just above 100 Hz, the self noise of the system from 20 Hz to 100 Hz has an **average** value of 47 dB above $1\mu Pa^2/Hz$. For this bandwidth of 20 Hz to 100 Hz, the **integrated** noise rises to about 70 dB vs $1\mu Pa^2$. Regarding the "signal:" the atmospheric attenuation at 15 km is only about 4 dB. Furthermore, the helicopter noise is band-reduced by about 6 dB. This adds up to a 10 dB reduction, giving a net value of noise-signal equal to 67 dB vs $1\mu Pa$. This design will therefore fail. So other designs must be looked at.

ADDENDUM

A DESIGN EXAMPLE OF A HOLLOW-CYLINDER PIEZOELECTRIC CERAMIC HYDROPHONE

Both (Langevin, 1954) and (LeBlanc, 1978) derive the microphone or hydrophone sensitivity $M = v/\mu Pa$ for a radially poled, end-capped hollow-cylinder as:

$$M = \frac{v}{p} \text{ or } \frac{\text{volts}}{\text{pressure}} = b\left[g_{31}\frac{2+\rho}{1+\rho} + g_{33}\frac{1-\rho}{1+\rho} \right]$$

where

b is the outer radius of the cylinder,

a is the inner radius of the cylinder,

ρ or β is a/b,

g_{31} is the transverse g-constant in v/m // N/m^2, and

g_{33} is the parallel g-constant, also in v-m/N.

Let the lead zirconate titanate ceramic tube have dimensions:

OD = 0.75"
b = 0.375" or 9.5 E-3 meters
a = 0.313"
L = 0.55" or 13.9 E-3 meters
t = 1/16"

The ceramic tube is radially poled and has capped ends. The ceramic material will be Navy Type II-m (PZT-5H Type). This has: $K_{33}^{T} \simeq 3400$; $g_{31} \simeq -11.1$ E-3 m^2/N; $g_{33} \simeq 24.8$ E-3 m^2/N.

Now $\rho = 0.835$.

$\frac{2+\rho}{1+\rho} = 1.54$; $\frac{1-\rho}{1+\rho} = 0.09$. (When this last ratio $\simeq 0$, the g_{33} term can be neglected and we have $M \simeq 3/2\ b\ g_{31}$).

Then $M = 145.6 \times 10^{-6}$ v/Pa, or

$145.6\mu v/Pa = -76.7$ dB vs $1^{V}/Pa$

which is -196.7 dB vs $1^{V}/\mu Pa$.

There are two resonances: longitudinal or f_{ℓ} and radial or f_r. We use the frequency constant $N_{3t}^{D} = f.\ell$ cycle-meters/sec. For Type II this is about 2000 cycle-meters/sec. The velocity alone is 4000 meters/sec. The mean circumference is $\simeq$ 55 E-3m and this equals one wavelength. Hence, the radial resonance $f_r \simeq 72,700$ Hz. (The longitudinal resonance f_{ℓ} is much higher and $\simeq$ 143,000 Hz).

The capacitance of the hollow cylinder is:

$$C = \frac{2\pi\ K_{33}^{T}\ \varepsilon_o L}{\ln(b/a)} = \frac{2\pi \times 3400 \times\ 8.85E-12 \times 13.9E-3}{\ln\left(\frac{.375}{.313}\right)} \text{ farads}.$$

Then C = 14.4 nF.

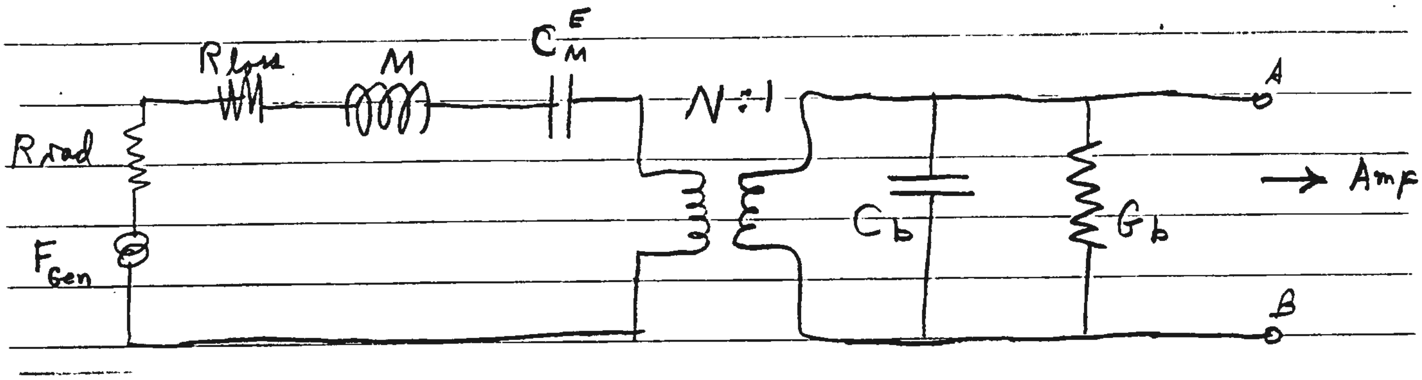


Figure A-1. Useful Analog Circuit for a Piezoelectric Microphone

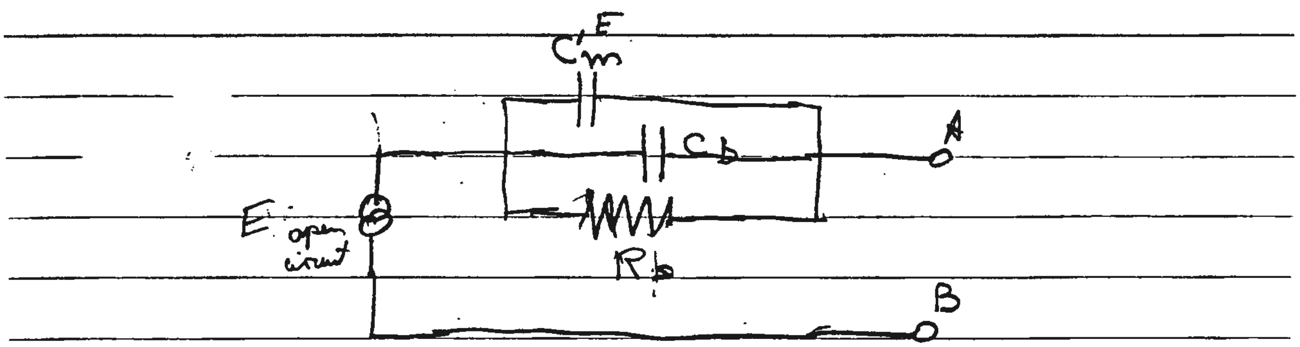


Figure A-2. Thévenin Equivalent of the Analog Circuit at Low Frequencies

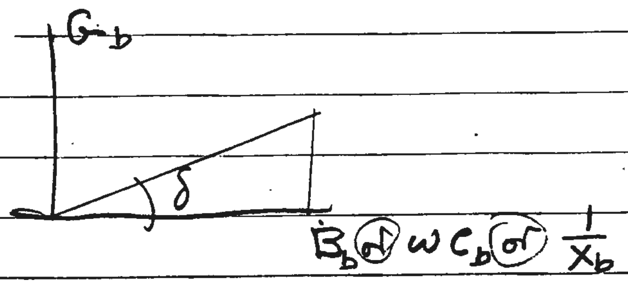


Figure A-3. Graphical Representation of tan δ = G/B

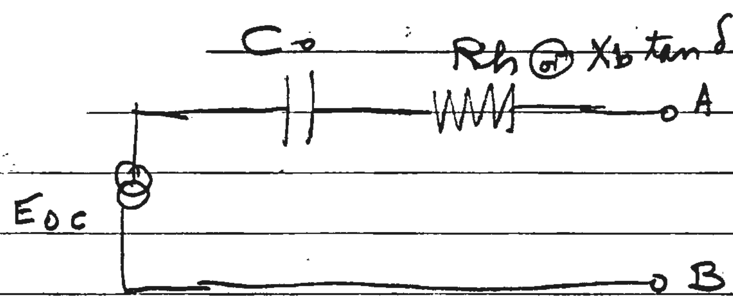


Figure A-4. Most Reduced Form of Analog Circuit for Microphones

5.1 AMBIENT NOISE

The spectral levels of underwater ambient noise, as summarized by Wenz,(1) are shown in figure 5-1. The lower limit of water noise is that contributed by the thermal agitation of the water molecules; this becomes significant practically at frequencies above 40 kHz. At frequencies below 40 kHz, there is a great deal of excess noise in the sea, caused by wave action and shipping plus minor contributions from numerous other phenomena.

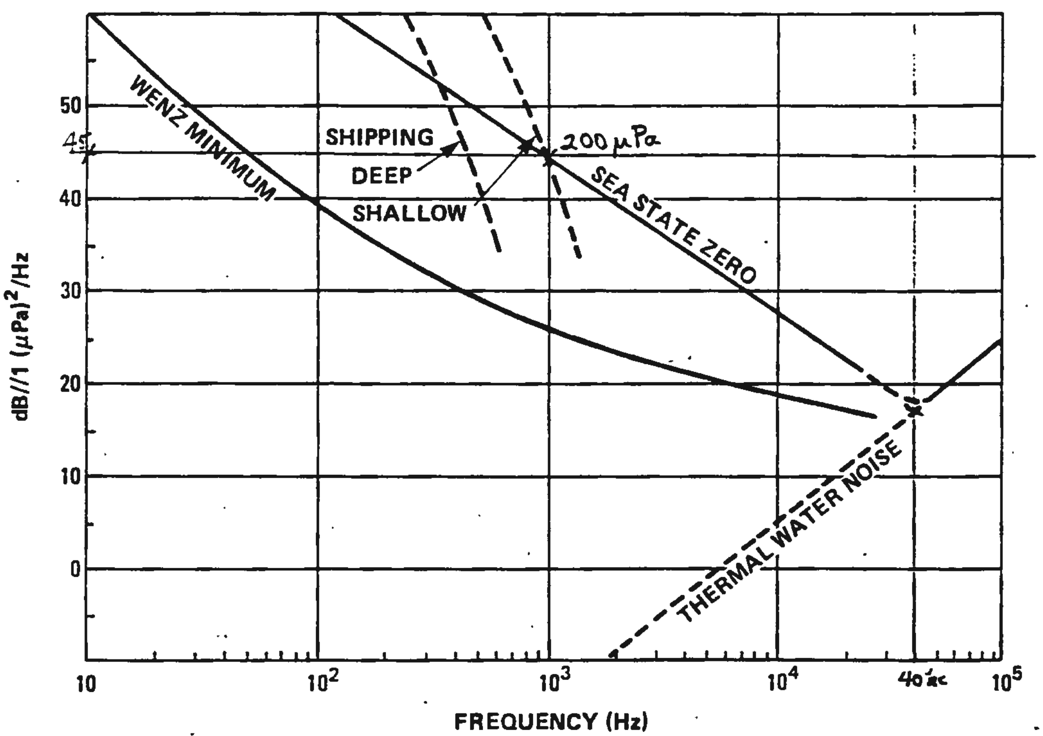
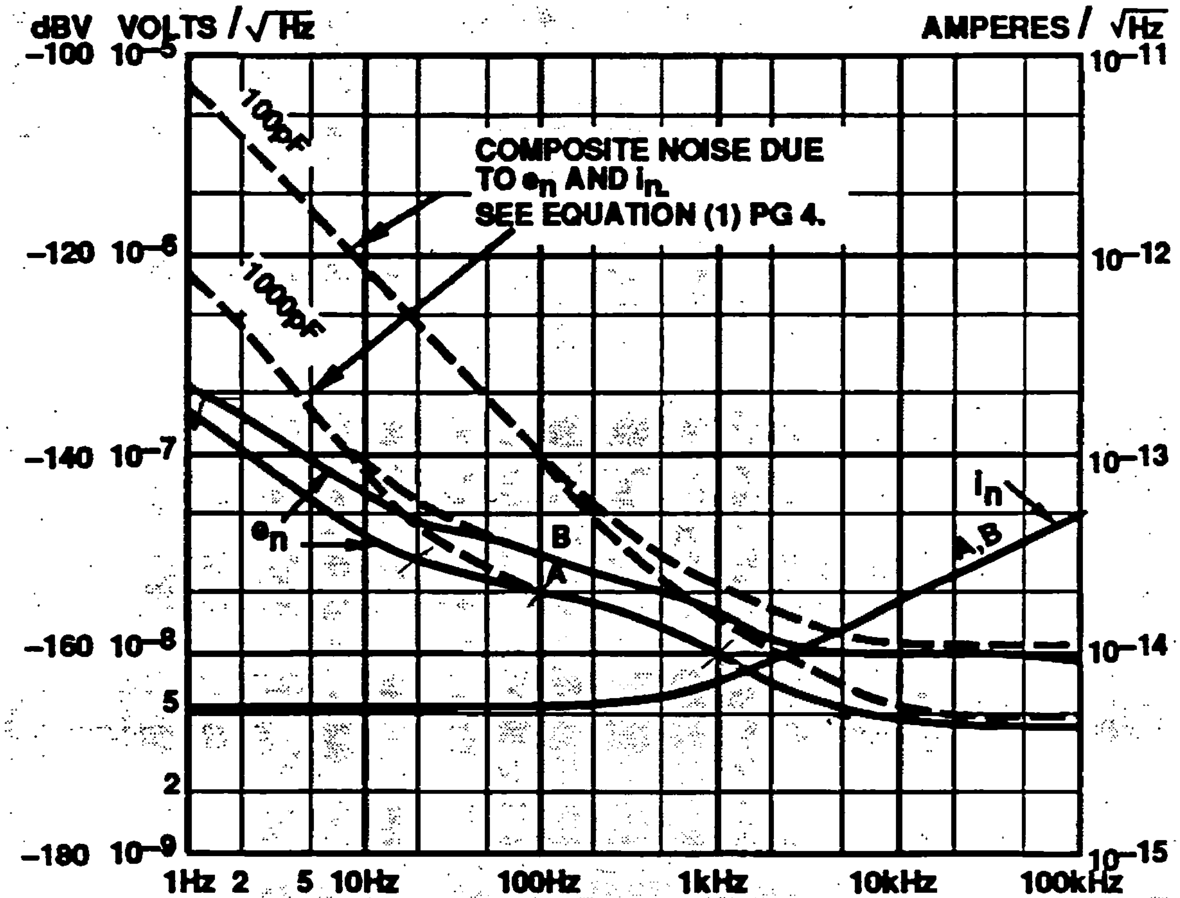


Figure A-5. Underwater Ambient Noise Curves

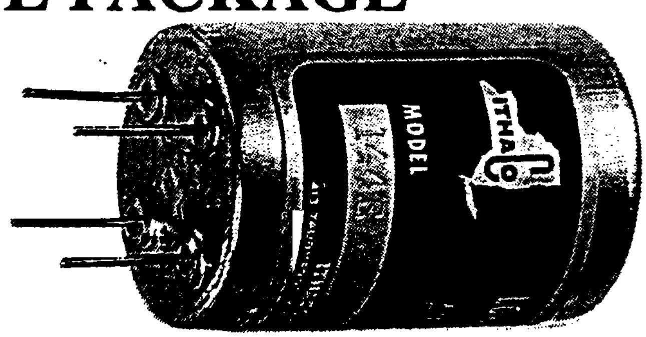
100 SERIES ULTRA HIGH IMI



√ $\boxed{\text{A}}$ refers to Models 143/144, B refers to Model 125

Noise Voltage and Noise Current For High Impedance Voltage Preamplifiers, 1 Hz BW

E PACKAGE



PIN CONNECTI

O OUTPUT

B POWER

I INPUT

G GROUND

CAN SIZE 29mm dia, 41mm long (1.13" Dia., 1.6" long)

Figure A-6. Noise Curves for Low-Noise Preamplifier (ITHACO Model 143/144)

Helicopter Noise Research

what happens if the rotor is slowed down. This was done by using a special engine governor.

Slowing the tip speed from 700 feet per second (fps) to as low as 510 fps made a significant difference in the noise of an approaching MD 500E (**Figure 28-3**). Going away, the change in rotor speed made little difference.

The experimenters were pleased with the results, but pointed out that lowering the tip speed also reduced the chance of making a safe entry into autorotation in an emergency. They suggested that if this scheme were used, the helicopter would require some auxiliary means of supplementing the rotor inertia. (It is not clear whether this recommendation applies to a helicopter with more than one engine.)

Sikorsky's noise-reduction research used wind-tunnel models with various blade-tip shapes for both main and tail rotors. By spreading out the tip vortex, a significant reduction in main rotor-blade/vortex interaction noise was obtained. In addition, a tip shape was found for the tail rotor that reduced its noise signature (**Figure 28-4**).

Figure 28-3
Helicopter Noise At Various Rotor Tip Speeds
MD 500E During 80-Knot Flyover

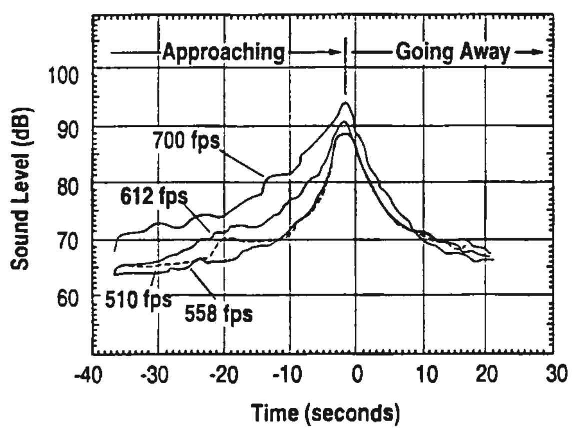


Figure 28-4
Sikorsky's Quiet Tip S-76 Tail-Rotor Blade

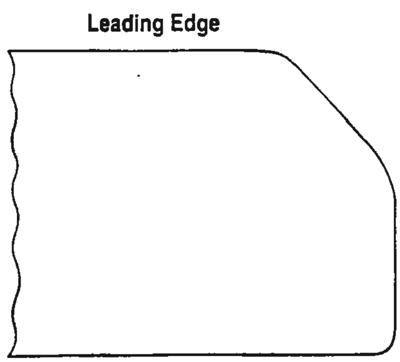
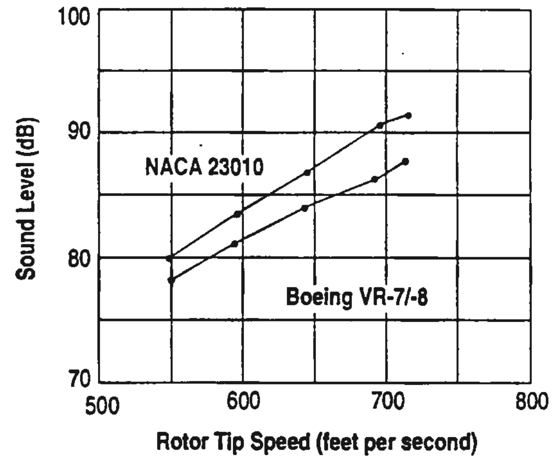


Figure 28-5
Effect Of An Airfoil Shape On Sound Level



For its part, Boeing Helicopters discovered that the type of airfoil had an effect on noise. **Figure 28-5** shows the difference in noise between a rotor with the old NACA 23012 airfoil and a second generation Boeing rotor with the VR-7 and VR-8 airfoils. It is not clear how this conclusion applies to the slab-sided airfoils that have been used on all recent rotor designs.

NASA experimented with ways of reducing blade vortex interaction (BVI) noise by using active control—a variation of Higher Harmonic Control proposed for reducing vibration. The results indicated that this could reduce the BVI noise by up to 5 dB.

NASA also looked at ways of reducing internal noise by introducing an audio system that produced equal and opposite sound waves to those coming from the helicopter. (This "noise-canceling" concept is already being used in some earphone systems.)

Criteria development

The final task to develop criteria was assigned to the FAA. The agency surveyed existing helicopter operations and studied the results from the program's participants to develop a set of helicopter-noise regulations to replace those it had prematurely proposed.

Presumably, by the time the regulations are official, the engineers will know enough to "design-to-noise" for all their future projects.

Related materials in *Helicopter Aerodynamics:* Chapter 31 and *More Helicopter Aerodynamics:* Chapter 25.

Figure A-7. Helicopter Noise During 80-Knot Flyover

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4. (a) John Crane BELFAB, Daytona Beach, Florida 32120. Tel: (904) 253-0628; (b) Servometer, Inc., Cedar Grove, New Jersey. Tel: (201) 785-4630. (Design manuals are available from both companies.)

5. Useful Talks With P. LeMesurier, Sikorsky Aircraft, Trumbull, CT; F. Farassat, NASA-Langley Research Center, Hampton, VA; S. Briggs, Naval Undersea Warfare Center Detachment, New London, CT; and M. Moffett, Naval Undersea Warfare Center Detachment, New London, CT.

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